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COORDINATION DYNAMICS OF THE COMPLEMENTARY NATURE

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Summary

Niels Bohr's maxim *contraria sunt complementa* indicated his strong suspicion that the complementarity interpretation of quantum mechanics might someday be expanded into a generalized principle. It now appears that such a principle has been found in metastability which appears at the scale of living things. Metastability has been proposed as a principle of brain~behavior, and is captured in the extended or 'broken-symmetry' version of the HKB model of coordination dynamics. The metastable regime of coordination dynamics reconciles the tendency of specialized brain regions to express autonomy (segregation) and their simultaneous tendency to work together as a synergetic whole (integration). There is growing evidence from recent studies in the brain and behavioral sciences that the complementary nature of integrating and segregating tendencies is essential to the way human brain~minds work.

Keywords

Binding problem; brain~behavior; complementary pairs; coordination dynamics; Niels Bohr; generalized complementarity principle; metastability; metastable regime; mind~brain; multistability; nonlinear dynamics; relative phase; tendencies; the squiggle symbol (~)

1. Prolegomenon

This essay introduces a novel perspective of contrariety that we call the "philosophy of complementary pairs" (Kelso & Engstrøm, 2006). Complementary pairs are those things, events and processes in nature that may appear to be contraries but are mutually related and inextricably connected. Such complementary aspects are dynamic and relational; both aspects of a complementary pair are required for an exhaustive account of phenomena. The symbol of the complementary nature relating contrarieties, opposites and their kin is the tilde or squiggle (~). A most intriguing and motivating aspect of this perspective is that it has been successfully grounded in the science of coordination dynamics, and is closely tied to its signature set of phenomena, especially *metastability*. In this context, we study the significance of metastability to complementary contraries and vice-versa. Interest in metastability both as an important observable phenomenon and as a useful conceptual framework is growing rapidly, especially in the neurosciences where it appears to be the result of the brain's self-organizing nature. According to coordination dynamics, nonlinear coupling among heterogeneous individual coordinating elements is necessary to generate the broad range of observable brain~behavior that includes self-organization, pattern formation, multistability, transitions, switching without switches, hysteresis and metastability (Kelso, 1991, 1995). In the so-called extended HKB model of coordination dynamics (Kelso,

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Delcolle & Schöner, 1990) metastability is produced as a result of broken symmetry in the relative phase equation that models patterns of coordination between nonlinearly coupled, nonlinear oscillators (Haken, Kelso & Bunz, 1985; Kelso, et al., 1990; Schöner, Haken & Kelso, 1986). Behaviorally speaking, the metastable regime of coordination dynamics appears to reconcile the tendency of specialized brain regions to express autonomy (segregation) and the simultaneous tendency for those same regions to work together as synergies (integration). While integration~segregation is an important and representative complementary pair, it is just one of many complementary pairs to emerge in the science of coordination dynamics.

2. Complementary Pairs

The human sense of contrariety is ubiquitous. Human experience teems with perceived contraries, like whole~part, self~other, nature~nurture and body~mind. Because contrariety is so pervasive in human experience, it has been widely believed throughout history that understanding its basic nature should lead to a deeper understanding of how nature works. As such, interpretations of contrariety have played an important role in the history of ideas. For example, the dualist stance epitomized in the writings of Descartes and his followers has had a dominant influence on our modern conception of brain and mind as separate entities—perhaps a little too much influence. Today's newspapers are filled with stories of extreme polarization of groups and their ideologies, as well as the continued detrimental spectre of intransigence that it so often generates. For example, in the neurosciences the dualistic counterposition of parts and localized function versus wholes and global processing, of neural segregation versus neural integration, continues to create major obstacles to advance. Now as ever, there is a palpable necessity to understand contrariety.

Some guiding questions to ponder in this context include: 1) Why do human beings routinely divide their world into contraries? 2) Why are contraries so often interpreted as being mutually exclusive, either/or dichotomies such as whole versus part, self versus other, body versus mind, nature versus nurture? 3) What is the ultimate nature of contraries and contrariety? Are contraries physical phenomena, mental phenomena, or somehow *both*? Pauli eloquently anticipated the position we support (Kelso & Engstrøm, 2006; Kelso & Tognoli, 2007; Pauli, 1994).

> "To us the only acceptable point of view appears to be one that recognizes both sides of reality—the quantitative and qualitative, the physical and the psychical—as compatible with each other. It would be most satisfactory of all if physics and psyche could be seen as complementary aspects of the same reality."

Variations of Pauli's perspective have reoccurred repeatedly throughout history. It is immortalized by Niels Bohr's famous maxim *contraria sunt complementa*—contraries are complementary (Kelso & Engstrøm, 2006). While Bohr himself viewed his maxim as a general epistemological position, most of his friends and colleagues saw it as a "fond hope", one unlikely to actually be realized. Nevertheless, one might assume as Bohr did that the great success in demonstrating the essential complementarity of quantum mechanics would eventually lead to an organized search for a generalized scientific complementarity principle. Curiously enough, up until recently, it hasn't. This point is concisely summarized by Michael Turvey (in Kelso & Engstrøm, 2006):

> "To date, Bohr's generalized complementarity principle has been no more than an epistemological stance with little to say to the scientist expressing a normal interest in predicting natural phenomena…"

Why is this? What seems to be the difficulty in pursuing this line of research? It is ironic that a major stumbling block impeding progress in discovering a general principle of complementarity of contraries appears to be the tenacious human habit of dichotomizing life into contraries in the first place. Once human beings have fragmented life into dichotomies, contraries and opposites, they have a tough time putting them back together again.

There are at least two significant differences between the metastability found in coordination dynamics and the complementarity of quantum mechanics relevant to pursuing such a generalized complementarity principle (Kelso & Engstrøm, 2006, pp. 81–85): 1) In quantum mechanics, complementarity means that radiation can behave as either a wave or a particle but never both at once, while in metastability, *tendencies* for contrary behaviors like segregation and integration coexist simultaneously. 2) Complementarity is theoretically bounded by the invisible dimensions of the quantal scale, while metastability is present in complex systems, including but not limited to the level of human brain and behavior. As such, we treat metastability as a strong candidate for a generalized principle of the complementary nature. We follow the premise that ubiquitous complementary contraries, which we refer to as *complementary pairs*—are coexistent, inextricable, and dynamical. By dynamical, we refer in general to their formation, persistence and change, adaptation and dissipation. It is important to note that in our work the word *dynamics* also has a meaning over and above its normal usage, namely it refers to the evolving, self-organizing and informationally meaningful coupled dynamical systems studied in the field of coordination dynamics. In both coordination dynamics and the philosophy of complementary pairs, the squiggle character (~) signifies the symbolic punctuation of reconciled complementary pairs, as in whole~part, competition~cooperation, integration~segregation, time~space, and body~mind. The (~) character is neither trivial nor is it a fancy hyphen, but rather an indication of the complex, relational and complementary dynamics that exists between complementary aspects (Kelso & Engstrøm, 2006).

Complementary pairs entail bistability, which can be appreciated intuitively from our general syntax of an arbitrary complementary pair ca1~ca2, where **ca** stands for **c**omplementary **a**spect, and the '~' or squiggle symbol stands for the complementary nature between and including them. To have a complementary *pair* at all, a system must be minimally capable of producing both ca1 and ca2. Bistability and more generally multistability is well known and plays a wide assortment of roles in many fields of research. It engenders notions of threshold and transition dynamics, and is certainly an important aspect of the complementary nature, though not the only one, as we will discuss below. As mentioned, metastability is a different, more flexible kind of dynamics that is essential to our definition of complementary pairs. In metastability, the tendency for individual coordinating elements to exhibit collective behavior coexists with the contrary tendency for those elements to express individual independent behavior. Our interpretation of complementary pairs predicts that a dynamical system can produce ca1 alone, ca2 alone, both ca1 and ca2, it can change from ca1 to ca2 and ca2 to ca1, and can also be neither—something above, beyond and different from all of these other possibilities. The grounding of this interpretation of complementary pairs in coordination dynamics lends the advantage that all of these behaviors are captured within its paradigm and methodology both as theoretical concepts and observable phenomena. But what is coordination dynamics?

3. Coordination Dynamics

Coordination abounds in the living world, as seen in the emergence of morphology from genetic instructions, movement from the action of joints and muscles, cognition from nerve cells, and social coordination patterns of people (Sporns, 2007). Coordination dynamics is a science of coordination that has solid roots in physics, mathematics, psychology and neuroscience. This science uses the concepts, methods and tools of informationally based, self-organizing dynamical systems (Fuchs & Jirsa, 2008; Jirsa & Kelso 2004; Kelso, 1995;

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Kelso & Engstrøm, 2006; Tschacher & Dauwalder, 2003). It has resulted in a set of context-dependent laws or rules that describe, explain and predict how coordinated patterns form and transform within~between individual coordinating elements of natural systems and within~between different levels of description. Core concepts include self-organization, dynamic patterns, pattern dynamics, multi- and metastability. These provide a tenable, testable explanation for the generation of patterns on several levels and their modification by functional information. Coordination dynamics deals with informationally coupled systems in nature, which means that information is actively used to coordinate things. This distinguishes coordination dynamics from other theories of self-organization which may include measures of information but do not actually use contextual, meaningful information as a basis for self-organization. It is about informationally based dynamic patterns and informationally based pattern dynamics (Kelso, 1994).

The foundational notions of coordination dynamics were initially inspired by the principles of synergetics (Haken, 1983; Haken, Kelso & Bunz, 1985) and subsequently adapted and extended to handle various experimental observations in the behavioral and brain sciences (Kelso, 1995). The concepts of self-organizing pattern formation and pattern dynamics are essential complementary aspects of this approach. In the scientific paradigm of coordination dynamics, one of the main coordination variables that changes qualitatively under parametric changes is the relative phase. In fact, relative phase proves to be a key quantity or *order parameter* (Haken, 1983) that captures spatiotemporal order in biological systems (Kelso, 1995; Kelso & Engstrøm, 2006; Kelso & Tognoli, 2007). Relative phase emerges as a result of nonlinear interactions among coordinating elements, yet reciprocally conditions or “orders” the behaviour of those same elements. The idea that the variable that changes qualitatively is the one that captures the spatial~temporal coordination in experimental data goes back to earlier theoretical modeling by Haken, Kelso & Bunz (1985) and is referred to in the literature as the HKB model of coordination dynamics. Using the concepts of self-organization and the mathematical tools of dynamical systems, in coordination dynamics the relationship between control parameters and values of the coordination variables is represented as a ‘hyperplane’ in phase space to delineate regions of stability and zones of transition (bifurcation) between them (Figure 1). In the simplest, extended or broken symmetry formulation of the HKB model (Kelso, et al., 1990) metastability corresponds to a dynamical regime near saddle-node or tangent bifurcations where stable coordination states like synchronization of relative phase between coordinating components gives way to metastable tendencies. In metastability, no stable or unstable fixed points remain, yet dynamical remnants of attractor~repellors linger, giving rise to a dynamical flow consisting of alternating phase trapping and phase scattering (see Kelso, 1995, ch.4).

4. The Extended HKB Model of Coordination Dynamics

The equation governing the coordination dynamics of the extended HKB model (Kelso, et al., 1990) describes changes of the relative phase over time as:

$$\dot{\varphi} = \delta\omega - a\sin\varphi - 2b\sin(2\varphi) + \sqrt{Q}\xi t$$

where ‘φ’ represents the relative phase between (for simplicity’s sake) two interacting components, *a* and *b* are parameters setting the strength of attracting regions in the system’s dynamical landscape, $\sqrt{Q}\xi t$ is a noise term of strength Q, and δω is a symmetry breaking term due to heterogeneity—each component has its own intrinsic behavior. The introduction of this symmetry breaking term δω changes the entire dynamics such as the layout of the fixed points and bifurcation structure of the original HKB system. It is the subtle interplay between the coupling term (k=b/a) and the symmetry breaking term δω that gives rise to metastability. What does coordination behavior look like in this metastable regime? Although all fixed points have vanished, there are still some traces of coordination, 'ghosts' or 'remnants' that occur where the fixed points once were (Figures 1b, 2c). This results in unique dynamics that may be captured by two types of behaviour in the time evolution of the relative phase that can be quantified as *dwell* time and *escape* time. Escape times are observed when the trajectory of the coordination variable, relative phase, drifts or diverges from the horizontal. Despite the complete absence of phase-locked coordination, the behaviour of the elements in the metastable regime is not totally independent. Rather, the dependence between the elements takes the form of dwellings where the phase gathers near remnants of the fixed points. Metastability provides a theoretical explanation for the 'magnet effect' observed many years ago in histograms of relative phase by the eminent physiologist Eric von Holst (Kelso, 1991).

It can hardly be overemphasized that, it is the *symmetry breaking* property of the extended HKB model that leads to metastability and the new insights it affords. Can the brain make use of such a principle? Our thesis is that the ability of the system to coordinate or compute without attractors opens a large set of possibilities (Figure 2c).

Both a multistable regime with attractor and repellor states and a metastable regime with no states but rather attracting *tendencies* offer theoretical accounts of perceptual, behavioral and cognitive multistability. In the case of multistability, which attractor is reached in the multistable regime primarily depends on initial conditions. Once the system has settled into an attractor, a certain amount of noise or a perturbation is required to achieve a switching to another attractor. If control parameters such as attention or frequency are modified, a bifurcation or phase transition from multistable to monostable states and vice-versa may occur.

In contrast, in the metastable regime of coordination dynamics, successive visits to remnants of the fixed points are intrinsic to the time course of the system, and do not require any external source of input (Kelso, 1995). This is an important difference between multistability and metastability, and likely translates into palpable differences in fidelity of performance, as a system in its metastable regime isn't hindered by fixed point behavior, while a multistable regime is. An important point—especially for those who study multistable phenomena—is that the extended HKB model of coordination dynamics captures *both* multistability and metastability. In fact, multistability~metastability and states~tendencies are considered key complementary pairs of coordination dynamics.

4. Coordination Dynamics as a Science of Complementary Pairs

In coordination dynamics, metastability corresponds to a regime near 'saddle-node' or 'tangent' bifurcations (Figures 1 and 2), where stable coordination states between coordinating components give way to metastable tendencies. By definition, metastability isn't a 'state.' No stable or unstable fixed points remain, yet dynamical remnants of attractor~repellors linger, giving rise to a dynamical flow consisting of convergent 'phase trapping' and divergent 'phase scattering.' In both coordination dynamics and complementary pairs, metastability is not a state, but rather a disposition to behave. Likewise, the brief epochs of phase wandering in the metastable regime do not correspond to fully segregated behavior. Only when the system *switches* in~out of a state or tendency is functional information created~destroyed. Analogous to quantum mechanics, the necessary and sufficient condition for the emergence of information in coordination dynamics is metastability (Kelso, 2002; Kelso & Engstrøm, 2006). Conceptually speaking, metastability provides a unified picture composed of dynamic, coexistent, complementary tendencies.

General dynamical complementarity of ubiquitous complementary pairs has important and far-reaching implications. It suggests, for example, that the paradigm and methodology of coordination dynamics can be broadly applied anywhere contrariety is found. In coordination dynamics, coordination states and dispositions are functional and context-dependent. By residing in the metastable regime, coordination dynamics provides a system with a mechanism for the creation~annihilation of informationally meaningful coordination patterns. As an explanation of the multistability~metastability of complementary pairs, coordination dynamics qualifies as a candidate science for the complementary nature.

5. The Multistability of Brain~Mind

Coordination dynamics offer new mathematical principles of brain structure~function. Extending notions in which functional information lies in the transient coupling of individual coordinating elements and physiological significance given to specific phase-lags realized between coordinating elements, we have proposed that *phase relationships carry information*, with multiple attractors and attracting tendencies producing the complementary aspects that emerge in consciousness (Kelso, 1994; Kelso & Tognoli, 2007). In the simplest case, oscillations in different brain regions can lock in-phase with brain activities rising and falling together, or anti-phase with one oscillatory brain activity reaching its peak as another hits its trough and vice-versa. Furthermore, in-phase and antiphase are just two of many possible multistable phase states that can exist between different specialized brain areas depending on their respective intrinsic properties, broken symmetry and complex mutual influence. (In Figures 1 and 2, in-phase and antiphase patterns are the patterns observed near 0 and 180 degrees phase relationship, respectively.)

Coordination dynamics considers the oscillatory phase relations among distributed brain regions a prerequisite for a dynamic process of self-assembly or ‘binding’ to coherent networks (see Kelso & Tognoli, 2007 for an extensive review). Not only does the brain possess many different phase relations within and among its many diverse and interconnected parts, but it can switch flexibly from one phase relation to another (in principle within the same coalition of functional elements), causing abrupt changes in perception, attention, memory and action. These switchings are literally nonequilibrium phase transitions in the brain (Haken, 1996; Kelso, 1995; Kelso et al., 1992)—abrupt shifts in brain states allowing the brain the capacity to lock into one of many available stable coordinative states or phase relations. The brain dynamics can also become unstable, and switch to some completely different coordinative state. In the original HKB perspective, instability is a selection mechanism picking out the most suitable brain state for the circumstances at hand. Locking in and switching capabilities can be adaptive and useful, or maladaptive and harmful, and could apply as easily to a person suffering from an attention deficit as they could to the surgeon honing her skills. This highlights the crucial role context plays in determining the final behavioral outcome of a system with such flexible dynamical capabilities.

6. The Metastability of Brain~Mind

Ample evidence now exists in the brain and behavioral sciences that metastability is central to the way human brains~minds work (Kelso & Engstrøm, 2006; Kelso & Tognoli, 2007) and may turn out to be the way all effective complex organizations work. A rapidly accumulating body of research suggests that the key to understanding the complementary nature of the brain~mind and its ability to create~destroy functional information lies in the metastable regime of the brain’s coordination dynamics (Kelso, 1994; 1995; Kelso & Engstrøm, 2006; Kelso & Tognoli, 2007). As discussed above (cf. Figure 2) in experimental brain recordings, metastability is revealed by brief epochs of phase-locking synchrony interspersed in time with phase wandering. Theoretical modeling demonstrates that metastability arises as a result of two complementary forces: one is the coupling among neural ensembles that is typically mediated by reciprocal pathways in the brain; the other is the expression of each individual neural ensemble's intrinsic biophysical properties, typically oscillatory and heterogeneous in nature. This metastable mechanism for binding~breakdown may be realized neuobiologically by coupling neuronal populations, themselves composed of groups of Hodgkin-Huxley, conductance-based neurons (Kelso & Tognoli, 2007). As Fingelkurts & Fingelkurts (2004) note:

> "Metastability is an entirely new conception of brain functioning where the individual parts of the brain exhibit tendencies to function autonomously at the same time as they exhibit tendencies for coordinated activity (Kelso, 1991; 1992; 1995; Bressler & Kelso, 2001; Bressler, 2003)".

And further,

> "One may note that the metastability principle extends the Haken synergetics rules… Metastability extends them to situations where there are neither stable nor unstable states, only coexisting tendencies."

As predicted in the extended HKB model, in the metastable regime there are no longer any stable, phase and frequency synchronized brain~mind states; individual regions of the brain are no longer fully 'locked in' nor fully independent. It appears likely that metastable coordination dynamics underlies coexisting tendencies for functional integration and segregation on all levels, and attests to the brain~mind's inherently complementary nature (Bressler & Tognoli, 2006; Edelman, 2004, 2006; Edelman & Tononi, 2000; Freeman & Holmes, 2005; Friston, 1997; Kelso et al., 1995; Sporns, 2004; Varela, Lachaux, Rodriguez & Martinerie, 2001; Velazquez, 2005). In the metastable brain~mind, local~global processes coexist as real complementary pairs evolving in parameter space and real time, and do not simply represent identifiable polarized 'states.' As the Finglekurts remark, metastability is an entirely new conception of brain organization.

The prospect of the metastable brain~mind is enticing in that thoughts themselves could be envisioned as the creation~destruction of functional information in brain~world systems. This eventuality would be universally relevant, and would carry special significance to both philosophical and neurobiological mind~body debates and discussions. The grounding of metastability in coordination dynamics provides an unprecedented opportunity for philosophical ideas about the brain and mind to be explored and tested scientifically. For example, this new perspective puts either/or debates like brain versus mind, localizationist versus holist, and nativist versus empiricist in sharp relief. It explains how apparently contrasting properties of the brain may coexist and how they may be reconciled.

We are fond of saying that coordination in the brain is like a Balanchine ballet. Neural groups briefly couple, some join as others leave, new groups form and dissolve, creating fleeting dynamical coordination patterns of mind that are always meaningful but don't stick around for very long (Kelso, 1995). It is transient coupling~uncoupling tendencies among heterogeneous individual coordinating elements that underlie the workings of the brain~mind and its complementary nature, within individual brain regions and between cortical and subcortical areas. A considerable amount of work indicates that transient, short-lived phase-coupled oscillations within~between specialized areas of the brain provide a mechanism for neural integration (see Kelso & Tognoli, 2007 for recent review).

The classical view of phase-locked coordination prescribes that in synergetic systems each individual coordinative element loses its intrinsic behavior and obeys the dictates of the assembly. However, in the metastable regime, the tendency for independent activity of individuals is more continually preserved. Another interesting feature related to the absence of attractors is the ability of the system to exhibit more than one coordination tendency in the time course of its life. This property is reminiscent of the multistable regime with attractors, with the difference that no 'hard switching' (i.e. parameter dependent phase transitions) is required to glide from one state to the other.

But can the brain~mind make use of such a principle? Evidence of multistability and spontaneous switching in perception and action abounds at both behavioral and brain levels (Almonte, Jirsa, Large & Tuller, 2005; Başar-Eroglu et al., 1996; Hock, Kelso & Schöner, 1993; Keil et al., 1999; Kelso, 1984; Kelso, DeGuzman & Holroyd, 1991; Kelso et al., 1992; Tuller, Case, Ding & Kelso, 1994). Aside from the multistable regime with attractors undergoing phase transition, the metastable regime is also suitable to explain the observable brain~behavior (Kelso, 1995; Kelso & Engstrøm, 2006; Kelso et al., 1995). The tendencies of the metastable regime toward the remnants of the fixed points readily implements spontaneous reversals of percepts and behaviors described in these studies. From the perspective of coordination dynamics, the time a system dwells in each remnant depends on a subtle blend of the asymmetry of the components and the strength of the coupling. Such a mechanism provides a powerful means to instantiate alternating thoughts/percepts and their probability in both biological systems and their artificial models, for example as observed with optical illusions. Importantly, metastable coordination dynamics is no vague approximation. It has a very precise meaning that isn't about states at all, but rather a subtle blend of *both* integrative *and* segregative *tendencies*.

7. Conclusions

> "In our world of perceptions things come in pairs, such as particles and waves, yin and yang, black and white, yes and no, love and hate, light and darkness—there are no intrinsic maybes as there are in the atomic world" (Miller, 2002, p. 100)

Extensive research and development of coordination dynamics over the past twenty-five years has led to a novel perspective of contraries and contrariety, one that is firmly grounded in the science of coordination. Compelling evidence exists for the complementary nature of human brains and behaviour. Coordination dynamics reveals how the complementary pairs of our experience are produced as well as how this complementarity is manifested, what it does, how it behaves. Coordination dynamics explains scientifically how under well defined circumstances, a system produces complementary pairs that follow repeatable and predictable lawful dynamical patterns. Such patterns can and have been modelled mathematically and studied experimentally.

The phenomenological~conceptual spectrum of coordination dynamics provides a vocabulary as well as a rich scientific basis for the onward study of complementary pairs. Through its ability to explain the dynamics of real complementary pairs such as integration and segregation, individual and collective, competition and cooperation, coordination dynamics reveals the complementary nature in a novel and useful way. A major goal of this research is to ground the interpretation of all complementary pairs in coordination dynamics, a science that belongs to the complex everyday world of human brains and human beings.

Many of the most deeply puzzling phenomena confronting modern philosophy, science, and technology in the past, such as emergence, nonlinearity, multifunctionality, interaction, and context, can be understood using coordination dynamics. As a science of coordination in living things that deals in the currency of informationally meaningful variables, coordination dynamics provides an explanation and interpretation of complementary pairs that is neither metaphorical nor restricted to some priviledged level. The ability of coordination dynamics to explain dynamic contrarieties as complementary aspects as well as the creation of

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functional information points to a scientific foundation for complementary pairs. Polarized aspects may now be interpreted in light of the essentially nonlinear multistability~metastability of coordination dynamics, which is able to account for extreme division and polarization (bistability), the observed switching in emphasis from one contrary complementary aspect to the other (phase transitions, bifurcations) and coexisting, complementary tendencies (metastable dwelling~escaping).

Coordination dynamics is chock full of complementary pairs (see Kelso & Engstrøm, 2006, pp. 217–225 for the *base set* of complementary pairs from coordination dynamics). Knowledge of the complementary pairs of coordination dynamics can also lead to advances in the field of coordination dynamics itself. It is likely that complementary pairs are involved on many levels of description and analysis. From this perspective, complementary pairs of coordination dynamics are predicted to provide general insight into arbitrary fields, endeavors, systems, and levels, and thereby afford a deeper and wider understanding of the complementary nature. Research can be pursued in two main ways: 1) to study complementary pairs of coordination dynamics as they apply to research and development outside the field of coordination dynamics; 2) to study complementary pairs found outside of the field of coordination dynamics using the concepts, methods and tools of coordination dynamics. This idea that study of complementary pairs can advance coordination dynamics while the study of coordination dynamics can advance the understanding of complementary pairs may have far reaching consequences.

If the brain~mind is indeed organized around principles of complementarity and coordination dynamics, then the tendency to polarize and also to reconcile the world can be tied to metastability. To gain more understanding of the mechanisms of metastability, it seems necessary to invent new strategies that study metastable coordination patterns in different fields, systems and levels, and to establish criteria for the differentiation of state transitions and patterns of converging~diverging dwell~escape behaviours. Of course, much more will be accomplished as people come to appreciate the key role of metastability in the complementary nature, and the availability of coordination dynamics to study it. After over a quarter century's worth of theoretical and empirical investigation, metastable coordination dynamics stands as a worthy candidate for a generalized complementarity principle—an eventuality so elegantly predicted by Bohr so long ago.

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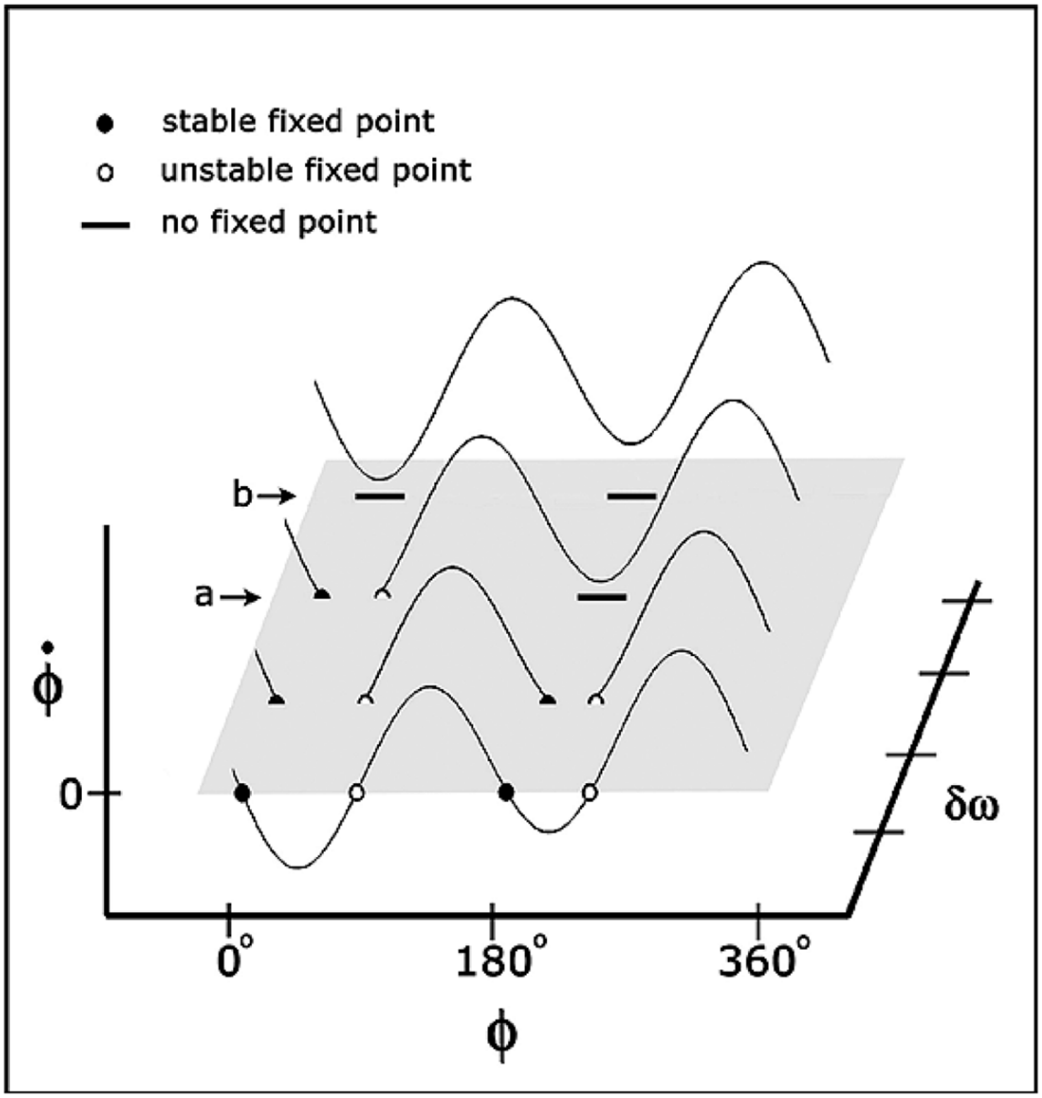

Figure 1.
Extended (broken symmetry) version of HKB coordination dynamics (Kelso, et al.,1990): The graph plots the rate of change of the coordination variable relative phase as a function of the relative phase value and a parameter δω representing the heterogeneity of individual coordinating elements. In this example the coupling is fixed. a) For fixed coupling and a certain value of δω, one of two stable fixed points dissipates, and the system changes from bistable to monostable. b) For fixed coupling and a higher value of δω, no fixed points remain, yet remnants or ghosts of the attracting and repelling fixed points remain. This is the metastable regime that underlies the coexistence of complementary pairs.

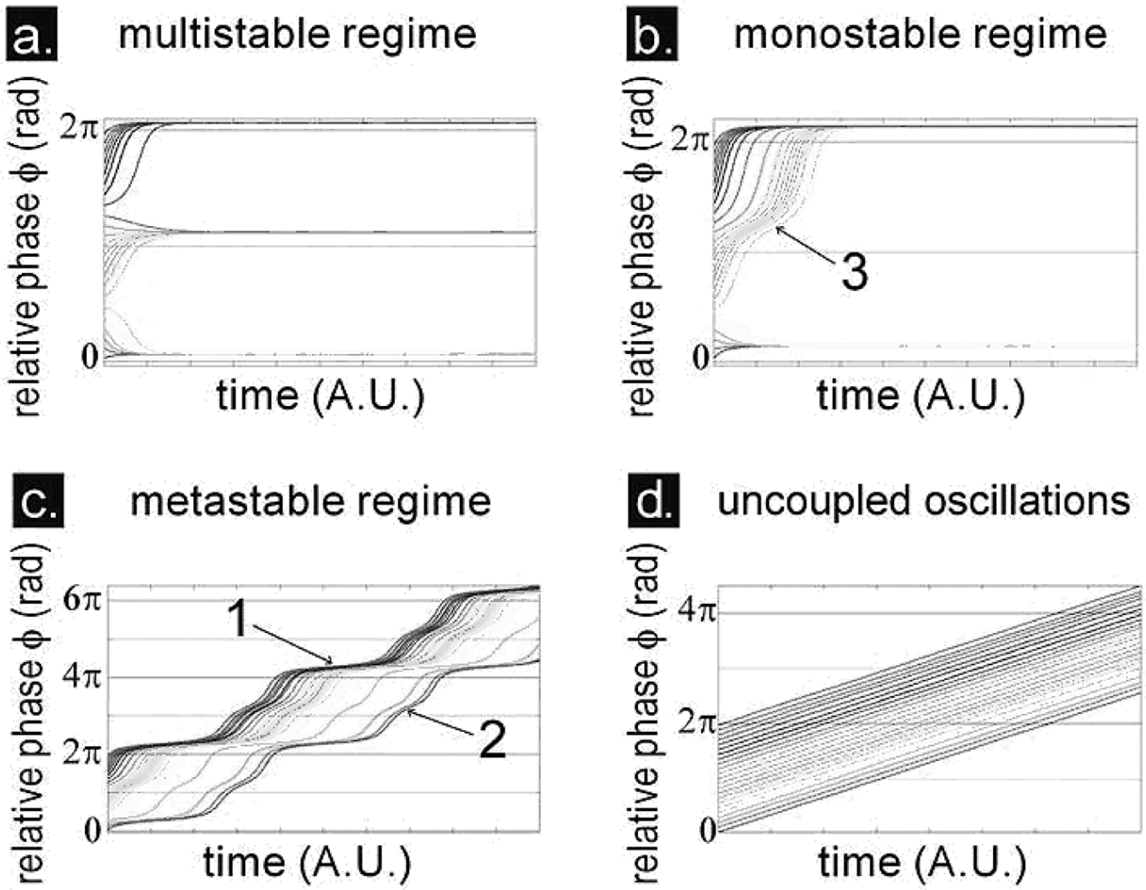

Figure 2. Multistability~metastability

Examples of 4 different types of dynamical trajectories of the coordination variable relative phase ϕ, arising from a range of initial conditions sampled between 0 and 2π radians. Multistable (a), monostable (b) and metastable regimes (c) of the extended-HKB model. (from Kelso & Tognoli, 2007). Notice how the metastable regime in (c) is in between the “pure” cases of multstability (collective states of coordination shown in a) and the totally uncoupled, individual behaviour shown in (d).